Programmable 2-Dimensional Microshutter Arrays

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ABSTRACT

We are developing a two-dimensional array of microshutters which can be used as a high efficiency, high contrast field selection device for a multi-object spectrometer for the Next Generation Space Telescope (NGST). The device is a close-packed array of shutters, with a typical size of 100 microns square and area filling factor of up to 80%. Each shutter, made of single crystal silicon with an appropriate optical coating, pivots on a torsion flexure along one edge. Each of the shutters is individually selectable. An original double-shutter mechanism is employed for actuation. Since the device works in transmission, there is no loss of contrast due to diffraction from the edges of unactuated pixels. When working in reflection, the device can also be used as a micromirror array.

Keywords: microshutters, micro-optics, spatial light modulator, programmable masks, micromirror arrays, planar structures, fabrication, actuation

1. BACKGROUND

With the advent of the micro electro mechanical systems (MEMS) era, the development of micromechanical array devices that allow redirection of light by individually controllable tiny mirrors, has been progressing at a fast pace. Practically all research and development programs in this area are concentrated on micromirrors. The task is extremely challenging and devices developed so far remain complex and expensive to manufacture.

An alternative approach to micromirror devices[1–3] are microshutter arrays.[4] Although advantages of the shutters for applications requiring high-contrast imaging are obvious, there have been no large array microshutters developed so far. Advanced arrays of microshutters, that are being developed and built by CSEM Co., Switzerland, have low area filling factor and small number of shutters (`http://www.csem.ch/microsystems/`). These devices employ a resonant excitation technique of the shutters and are designed for operation at room temperature. In astronomical applications micromirror and microshutter devices can be used as object selection devices for multi-object spectrometers. The Next Generation Space Telescope (NGST) gave a strong boost to these studies, in particular, in application to infrared astronomical spectroscopy.[5] Primary wavelength region of NGST operation is the near-infrared, and devices have to be cooled to cryogenic temperatures, which makes technological problems yet even more complex. Inspired by the development of the DMD (Digital Micromirror Devices) by Texas Instruments, two teams are currently developing micromirror arrays for the NGST.[6,7]

We decided to take an alternative to micromirrors approach to the problem and pursuing a goal of creating large fully addressable microshutter arrays of small elements (100μm typical dimension) with high efficiency (80% or better for the ratio of shutter area to the total area). From the optics point of view, transmissive masks are far better than reflective devices, because they provide much lower diffracted and scattered light and as a result achieve highest possible contrast. Microshutters, unlike micromirrors, require large angles of rotation of the individual microelements. This makes implementation of the high performance microshutter array more challenging compared to micromirrors. In micromirror arrays the area behind the mirrors is available for the structures providing actuation and addressing, whereas in microshutter design all these should be hidden in tiny support structures between the blades and/or on the blades themselves. A novel approach to the microshutter design together with an actuation mechanism and microshutters addressing opens an avenue to creation of efficient large format microshutter. Although these microshutters are being developed as cryogenic temperature devices for the infrared spectrometer on the NGST, they can also be used at optical wavelengths on the ground-based telescopes and other applications where field selection devices are required. Projection technique is one of the potential areas of application. Other possible applications are mass-spectroscopy and laser ranging. In mass-spectroscopy microshutters can be efficiently used for modulation of the ion source. In the laser they could provide fast changing attenuation of the optical signal that would help to expand the distance range.

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2. MICROSHUTTER DESIGN

Primary areas of the development include mechanical design of the shutter, actuation mechanism design and study of the mechanical performance of the device. Variations in the design, first of all in the geometry of the microshutters and support structure (including suspension), are a focus of this study along with exploration of possibilities of other areas of application.

2.1. Mechanical design

One of the key issues in the microshutter development is mechanical design of the single shutter. Combined requirements, of very large deflection angles of the blades, at least 90° and tight packing for high efficiency represent a great challenge. Requirement of random addressing and large sizes of the arrays further complicate the task. Mechanical design of the individual shutters should provide enough room for the addressing and engaging electronic circuits to fit onto the tight area of the shutter support structure and shutters themselves.

Shutters are designed with asymmetric suspension on a torsion bar attached to the shutter only in the middle (Fig. 1a). This design allows to have longer torsion bar and therefore reduces the stresses. Sample tests and mechanical analysis proved that this design allows full deflection of the microblade out of the light path.[8] Although such suspensions have been used in MEMS technology before,[1–3] previously developed devices usually did not require tight packing and/or large deflection angles.

The important advantage of this design over other designs is that it is simple to manufacture and cost effective. It doesn't require complex multicomponent cells, the whole shutter array can be manufactured by photolithography from one single membrane and is easily scalable to larger sizes.

2.2. Actuation scheme

A very important part of the design is actuation scheme. After examining various proposed solutions, we selected an actuation scheme which we call "double-shutter" (Fig. 1b). Double-shutter actuation allows it to translate macromotion of a large structure, the membrane itself, into micromotion of the shutters (Fig. 1b,c). To implement this, two identical microshutter arrays are rotated 180 degrees with respect to each other and brought in close physical contact. Addressing and selecting is performed electronically by applying a voltage between a shutter blade and its counterpart on the actuation membrane. Once blades are selected and engaged the whole actuation membrane is moved by the actuators located outside of the active area and all engaged shutters open. De-selection will cause an open shutter to return back into the closed position (Fig. 1c, last frame).

The advantage of this actuation scheme is that required mechanical components are relatively simple by design and fabrication. Both shutter arrays are made from a thin single membrane with embedded microcircuit and appropriate optical coating if required. Low stress of the torsion bars even at large deflection angles allows using relatively low voltages for shutters engagement, at the level of about 20 V. We tested this actuation scheme on a single element shutter (Fig. 1c). Next step will be testing the actuation of small size (five by five) arrays followed by manufacturing larger size arrays, 500 by 500 elements.

Another possible actuation mechanism involves resonant excitation of the individual shutters by applying a high frequency voltage between the selected shutter and an electrode. Once the oscillation amplitude reaches a required maximum, the shutters are locked electronically by applying a static voltage between the shutter and a holding electrode. This scheme, however, requires elaborate manipulation of the drive voltages and additional structures with locking electrodes standing perpendicularly to the shutter plane.

This addressing scheme is currently in the process of design and study. It will be accomplished dynamically by DRAM type circuit, addressing one microshutter at a time. Each engaged shutter can be considered as a tiny capacitor. Once it is charged by the addressing circuit and disconnected, the deposited charge will be holding the blades attracted to each other. We expect the hold time of the shutters to be long enough to have acceptably low required refresh rate. Multiplexing and dynamic addressing will greatly reduce the complexity of the embedded circuit.

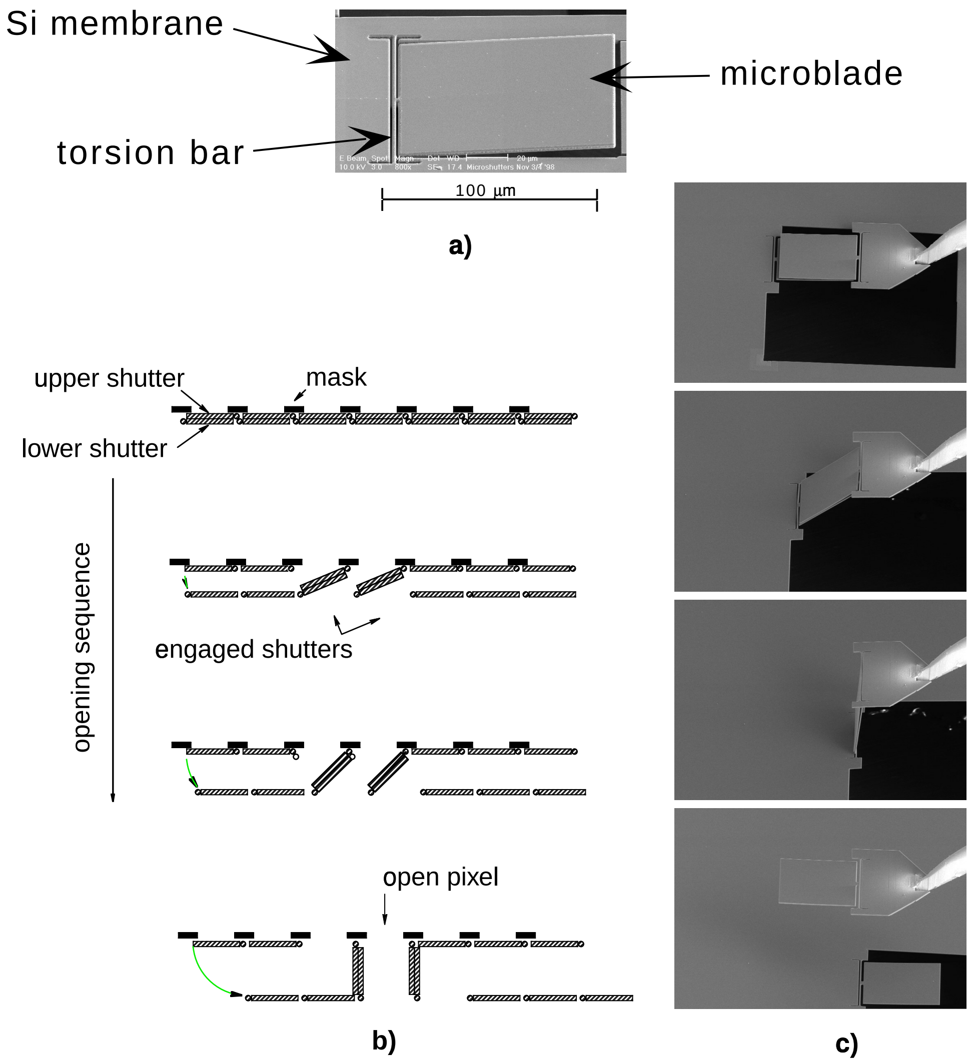
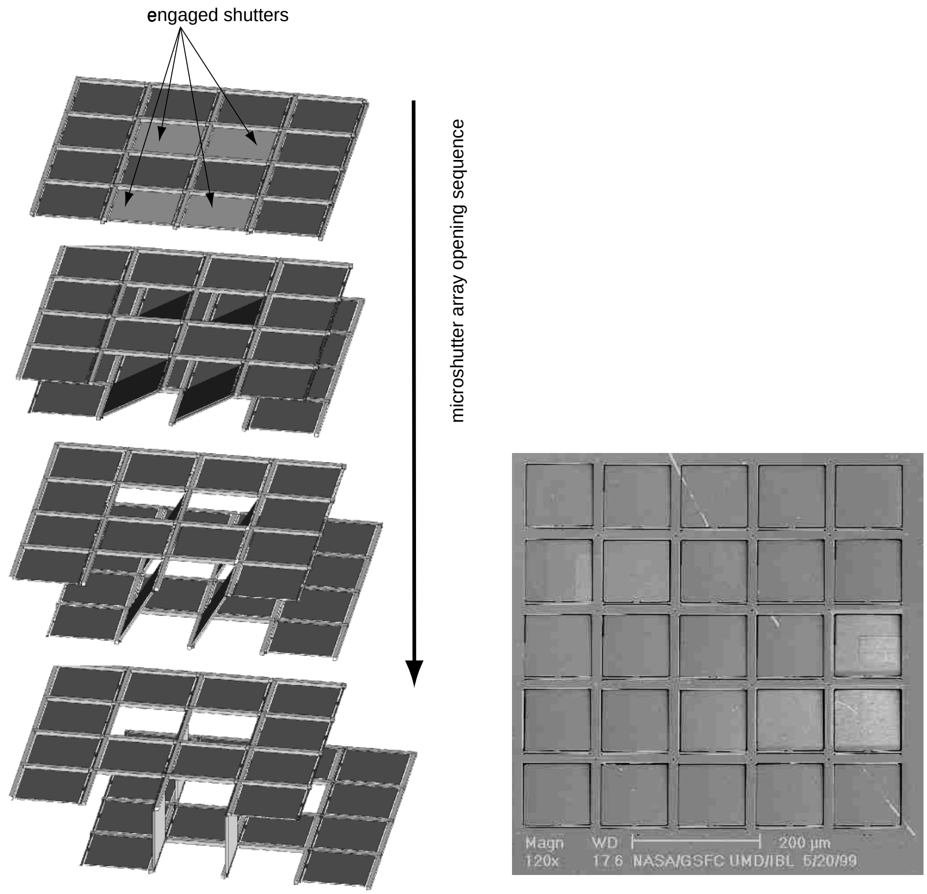


Figure 1. a) SEM image of a single shutter blade, b)Sequence of the microshutter opening (side view). Microshutter blades are represented by the shaded rectangles. Shaded circles are torsion bars. Two blades are engaged to have one pixel open, c) Opening sequence of the single shutter model. Shutters first are brought to close contact, and a voltage is applied to engage the shutters. The lower shutter is attached to the bulk of a membrane, the upper shutter is welded to a needle-manipulator. The upper shutter is moved along the arc formed by the radius-vector connecting their torsion bars. Frame three shows the shutter blades at 90° to the membrane (full open position). After the voltage is reset, shutters return to initial position (frame four).

3. EXPERIMENTAL SETUP AND TESTS

Unlike most of the MEMS devices, that involve multiple layer deposition and structuring processes, our concept of the microshutters is based on one homogeneous layer of high strength material, patterned during processing and used as a mechanically active layer. To carry out the tests of the proposed design, layers made from two different types of materials were examined. Both were prepared as free-standing membranes suspended on un-isotropically etched (KOH) silicon substrates.



a) b)

Figure 2. a) 3D sequence of the double-shutter actuation mechanism, b) SEM images of five by five microshutter array.

One membrane was single crystal silicon 2μm thick membrane, prepared as a silicon on silicon oxide layer. The membrane was thermally oxidized to about 50nm and had a one sided chromium layer of about 20nm. In another case the material was a low stress nitride layer of about 0.5μm with a one side aluminum layer of about 20nm.

The suspension tests (Fig.1) have demonstrated that the torsion beam allows blade deflection of up to 180 degrees.[8] The membrane can be single crystal silicon, silicon-nitride or any other material with sufficient strength. Experiments with both silicon and silicon nitride showed good mechanical performance of the shutter. The membrane is mounted on a frame, a structured wafer, which allows transmission through the shutters. To select and engage the shutters, the voltage is applied using an addressing microcircuit, which is implemented on the frame and the shutters themselves.

All microshutter manufacturing and experiments were carried out in a FEI 620 focused ion beam milling machine at the Lab for Ion Beam Research and Application (LIBRA), University of Maryland. This machine has proven to be a very useful tool for in situ testing of the manufactured devices.[8] The FEI 620 is a dual beam machine, with an ion and electron column which allows ion milling and situ scanning electron microscopy. Ion milling can be performed with ion beam spot sizes in the range from 20nm to 1μm. Machining rates in Silicon from $10^{-3}\,\mu\text{m}^3\,s^{-1}$

to 10 μm^3 s^{-1}. The machine is also equipped with a micro-manipulator needle and the possibility to deposit Pt by ion induced MOCVD. This combination turned out to be a perfect tool for a variety of experimental techniques:

- machining and observing structures virtually in real time,
- performing bending and moving tests, using the manipulator needle,
- analyzing shutter response time to a needle induced force by focusing an electron beam spot to a moving object and observing secondary electron time signal,
- machine electrodes, weld them to a needle by depositing Pt and use it to apply electrical forces to a machined microstructure,
- machine MEMS structures, weld them to the needle and use it for tests.

This setup allowed very quick turnaround in tests which, in turn, resulted in a fast development from the idea inception to the implementation, test, and refinement of the design. Within a few months we were able to progress from scratch to a fully operational single element microshutter. The shutters were brought in close contact, engaged by applying DC voltage, then moved to "open" position, when the shutter was perpendicular to the membrane plane, and then disengaged. Although all tests have been carried out at room temperature, there are no factors that would prevent these shutters from operating at cryogenic temperatures. Currently we are in the process of fabricating and testing small 2D-arrays of shutters (typical size 5 by 5 elements, Fig.2b).

Resonant frequency measurements allowed us to estimate the stresses in the shutters. Finite element analysis results agreed well with the measurements of the resonant frequencies and demonstrated uniform distribution of the internal stresses. Results of the analytical approximations are consistent with the results of the finite element analysis.[8]

4. SUMMARY

The device being developed in this project will be a large format mask for astronomical multi-object spectroscopy. Major achievement from the technological point of view is the solution of the large deflection angles problem and a close-packed array of elements. Combination of the double shutter actuation scheme with electronic addressing allows random shutter access. Since our device works in transmission, it achieves minimal scattered light and maximum possible contrast of the spectra. Although being designed for a specific goal in the infrared spectroscopy, these devices can find much wider application in such areas as projection technique, laser ranging and mass-spectroscopy. Our further plans include developing and testing small and then larger shutter arrays with typical size of 500 by 500 elements.

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